

NASA Technical Memorandum 100700

**Design Guidelines for Robotically
Serviceable Hardware**

(NASA-TN-100700) DESIGN GUIDELINES FOR
ROBOTICALLY SERVICEABLE HARDWARE (NASA)
23 p CSCL 13I

N88-25472

Unclas
G3/18 0149517

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April 1988

NASA

N88-25472 #

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Design Guidelines for Robotically Serviceable Hardware

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1988

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INTRODUCTION

Robots, particularly in the form of teleoperated systems such as the shuttle RMS, are proving to be invaluable tools in the on-orbit repair and assembly of spacecraft. However, current robotic technology is limited by the fact that a robot must either be taught the required actions prior to performing them or that it be used in a master-slave mode in which the robot mimics the actions of its human controller. The first scenario limits the use of robots to performing very repetitive tasks while the second scenario requires constant operator control. A more productive type of robot for space applications would be one that could be given a task and then autonomously determine how to carry the task out. The research into automation and robotics technology being conducted at the Goddard Space Flight Center (GSFC) is attempting to develop these capabilities.

The efforts of this research project can be separated into two major areas. The first area is the development of software which has the ability to generate robot instructions for servicing based on the information contained in a CAD data base. These servicing instructions are then carried out using force feedback to reconcile the real world with the CAD data. The second area of research is the development of guidelines for the design of spaceflight hardware that can be serviced robotically. While much of the effort in the development of on-orbit robotic servicing capabilities is directed at expanding the technology of the robots that will do the servicing, there is very little work being done to develop requirements for the design of the spaceflight hardware that is to be serviced. The research at Goddard is aimed at providing the guidelines necessary to design and build spacecraft systems that can be serviced by robots while in orbit. A mock-up which represents these guidelines will be used to verify and refine the servicing concepts being developed. The mock-up is based on existing spaceflight hardware to provide realistic design constraints. The mock-up along with the planning software will serve as a testbed for the concepts of autonomous robotic servicing.

This report will examine the design guidelines developed for robotically serviceable spacecraft and show how these concepts have been represented in the mock-up. The basic philosophy of robotic servicing and the ways in which this philosophy is reflected in the selection and development of the mock-up hardware will be studied. The report will also highlight the design features that make the mock-up "robot friendly" and examine how these features were affected by the design constraints of the hardware upon which the mock-up is based. The intent of this document is to provide insight into the formulation of design guidelines for robotic servicing and show how these guidelines have been used to develop a mock-up which will serve to validate and refine the concepts of autonomous robotic servicing.

DESIGN GUIDELINES

The design of robotically serviceable hardware is dependent upon many factors such as the environment in which the hardware is to be serviced and the type of robots used to do the servicing. The development of guidelines for the design of such hardware must reflect those factors. The design guidelines to be studied by this research were formulated based on the overall objective of developing autonomous on-orbit servicing capabilities. These guidelines are as follows:

1. All components must be constrained during servicing.
2. Two-handed servicing operations are allowed.
3. All fasteners must be captive.
4. Standard hardware should be used where possible.

The first guideline relates to the study of on-orbit robotic servicing methods as opposed to ground based techniques. Since the servicing operations being considered by this research are to be undertaken in a zero-G environment, gravity cannot be relied upon to hold objects in place. Therefore, components must be restrained at all times during servicing to prevent them from floating away. This means that objects being manipulated by the robot end-effector must be held so as to prevent a shift in position while in the robot's grasp and components being serviced must be secured against motion while restraining fasteners are either being put in place or removed.

The need to constrain component motion in a zero-G environment leads to different operational scenarios depending on whether the servicing is to be performed by one or two robot arms. If one robotic arm is used, then the end-effector must be able to securely grip the component and also operate its restraining fasteners. In two arm servicing, one arm restrains the component from motion while the other arm operates the restraints. Another difference between the two servicing methods is the way in which each handles fastener torque. One arm servicing reacts the torque back through the robot arm or end-effector which means gripping fixtures must be present at each fastener location. In the two arm operation, the fastener torques are not resisted by the robot arm used to operate the fasteners but rather taken up by the arm that is used to restrict component motion. This means that a single gripping fixture can

be used to restrain the component during servicing. The guideline to allow two-handed servicing operations was based on several considerations. The end-effector design can be made simpler and more compact because one robot arm does not have to perform the dual task of gripping the object as well as operating the restraints. Also, dividing the tasks of fastener operation and component manipulation has the least impact on the hardware design because a single gripping location can be used to constrain the component from motion.

The guideline to use captive fasteners is an attempt to minimize both the number of operations the robot must perform and limit the complexity of the tooling required to carry them out. If non-captive fasteners are used, the robot must grasp each fastener, remove it from the component, and place it in a storage rack. With captive fasteners, there is no need to manipulate each fastener separately. The robot must only be able to impart the force (or torque) necessary to operate the fastener. This simplifies the gripper design, cuts down on the number of operations required to accomplish servicing, and removes the need for a separate storage fixture to hold the fasteners.

The final guideline, which requires the use of standard hardware wherever possible, reflects an attempt to limit the effect that robotic servicing requirements have on the overall design of spaceflight hardware. One of the underlying efforts of this research is to show that the design for robotic servicing can be accomplished using existing technology and can be undertaken within the constraints currently placed on spacecraft design. Therefore, the fasteners, materials, and electrical connectors used in the mock-up are, wherever possible, components that are common in the design of spacecraft systems.

MOCK-UP DEFINITION AND FUNCTIONALITY

While the guidelines presented in the previous section define the focus of the research effort, it is the mock-up hardware developed from those guidelines that will represent their application to the design of robotically serviceable spacecraft. In order to ensure that the concepts of robotic servicing being developed are realistic in terms of actual design constraints, the mock-up was to be based on an existing spaceflight system. It was therefore necessary to choose a system that would provide the most effective mock-up for representing the design considerations based upon the type of robotic servicing being studied by this research.

Typically on-orbit servicing and assembly operations have been aimed at large spacecraft subsystems. The approach has been to modularize spacecraft into Orbital Replacement Units (ORUs) at a fairly high level and provide interconnects between modules and support structure. The electrical and mechanical connections are kept simple to permit a single point of operation and allow the ORUs to be easily disconnected and removed. The idea is to package complex components which cannot be serviced on the spacecraft in such a manner so that they can be easily replaced by an astronaut or robot and returned to earth for repair. This servicing approach has several drawbacks. The failure of any part within an ORU requires that the entire ORU be replaced. ORUs are typically single purpose in that they cannot be interchanged with other ORUs or used for other applications. Finally, the size of an ORU designed for servicing typically prohibits providing on-board spares.

In certain situations it is advantageous to be able to service spacecraft at a sub-ORU level. This is typically the case with the failure of electronic components within an ORU such as a power supply or a data storage unit. Servicing at this level will provide the ability to replace only the components that fail and also allow the on-orbit assembly of serviceable systems from available modularized components. The guidelines for robotic servicing being developed through this research are aimed at providing the ability to service spacecraft at the lowest possible component level. In order for the mock-up to serve as a realistic test of guidelines for the design of hardware to be serviced at this level, the system chosen as the basis of the mock-up had to consist of a number of small components that would be candidates for servicing.

Along with servicing considerations, two other criteria were used in the selection of the spacecraft system to be replicated by the mock-up. The system selected had to have clear and unchanging hardware requirements against which to build the mock-up. This ruled out any equipment that was still in the design phase because the hardware requirements would be affected by its evolving design. Secondly, the system chosen had to be complex enough to require a number of different servicing operations in order to thoroughly exercise the capabilities of both the planning software and the robot hardware.

SIC&DH DESCRIPTION

The system chosen to serve as the basis of the mock-up to study the guidelines for the design of robotically serviceable spacecraft was the Scientific Instrument Command and Data Handling (SIC&DH) unit of the Hubble Space Telescope (HST). The SIC&DH unit, shown in Fig. 1, is responsible for processing and storing data from the scien-

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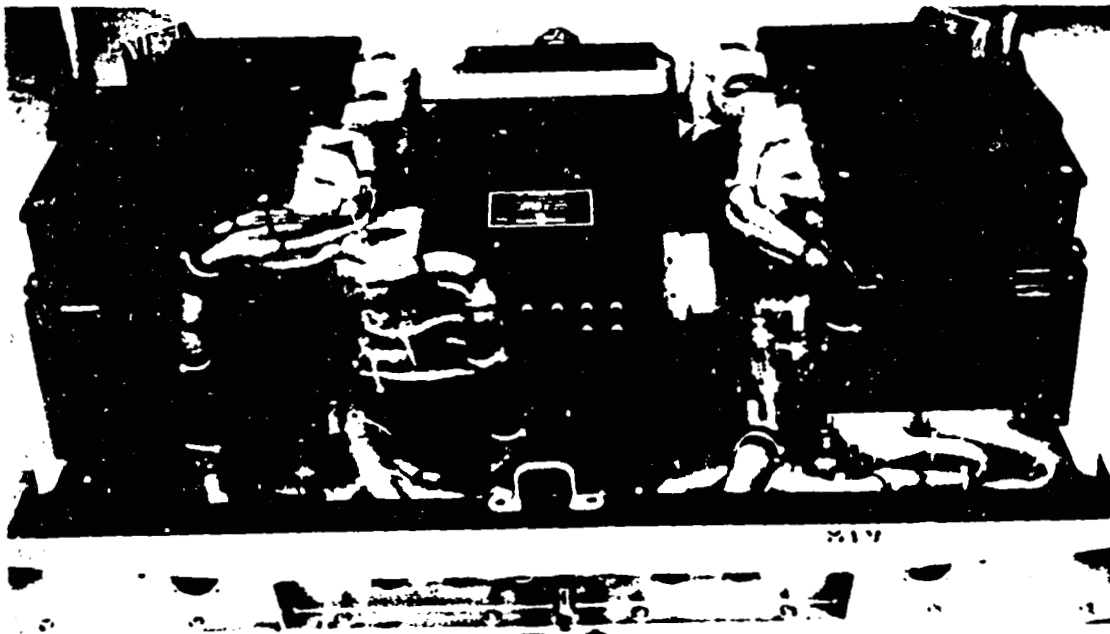


Figure 1. Scientific Instrument Command and Data Handling (SIC&DH) System of Hubble Space Telescope (HST)

tific instruments on HST and consists of several electronics modules mounted to a structural tray. The unit is one of several ORUs on the HST that were designed to be removed and replaced by an astronaut on EVA. The location of the SIC&DH ORU, which is mounted to the door of bay ten (10) of the Support Systems Module (SSM) equipment section, is shown in Fig. 2. The ORU is removed by loosening the ten captivated mounting screws that hold the ORU to the bay door and operating a jackscrew which serves to disengage the signal and power connectors on the ORU from corresponding mating connectors on the SSM. While the servicing of the SIC&DH as an ORU is a fairly simple task for a robot system, servicing the unit at the sub-ORU level provides a number of different and challenging tasks including the mounting of electronic modules to the structural tray and the mating of several different types of electrical connectors at various locations on the ORU. The electronics modules which make up the SIC&DH subsystem are as follows:

- Control Unit/Scientific Data Formatter (CU/SDF)—2 Req'd.
- Power Control Unit (PCU)—1 Req'd
- Standard Interface for Computer (STINT)—2 Req'd
- Central Processing Module (CPM)—2 Req'd
- Remote Interface Unit (RIU)—2 Req'd
- NASA Standard Spacecraft Computer Memory (NSSC)—8 Req'd

Fig. 3 shows the layout of these components on the structural tray. Also shown in this figure is the EVA handle by which the astronaut manipulates the ORU and the interface connectors which are fixed to a panel at the front of the ORU and connect it to the SSM. The PCU mounts directly to the ORU tray while the rest of the components are mounted in stacks at five locations. The memory modules mount to the tray in two stacks of four modules each. Two of the other module stacks consist of a CU/SDF with a RIU mounted on top. The fifth stack has the 2 STINTs and 2 CPMs assembled alternately. Interconnecting all the components on the tray is the wire harness which runs between the stacks and is responsible for the transfer of data and power between the SIC&DH modules as well as from the ORU to the HST spacecraft.

MOCK-UP DESCRIPTION

The mock-up serves to demonstrate and evaluate the guidelines developed for robotically serviceable hardware. The mock-up of the SIC&DH that was fabricated for this research is shown in Fig. 4. The SIC&DH mock-up represents the first attempt at the development of spaceflight hardware designed to be serviced robotically and serves as a tool for the further refinement of autonomous robotic servicing concepts.

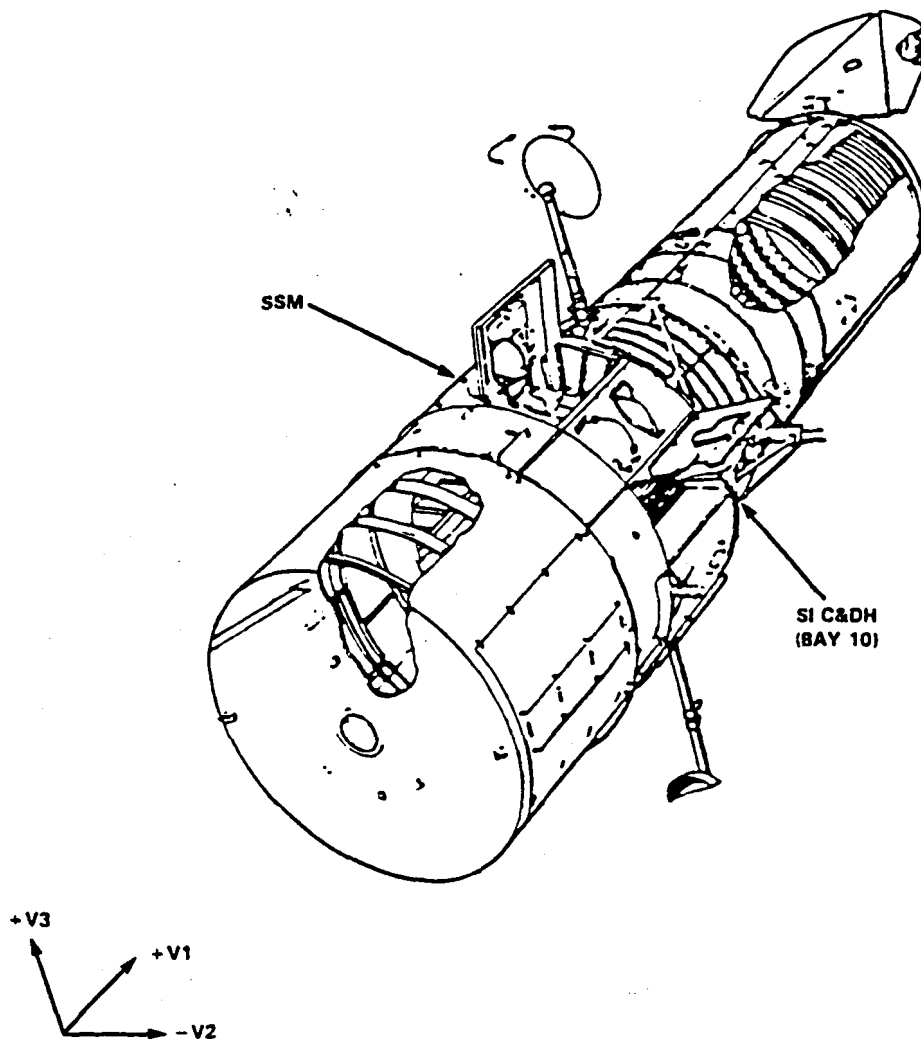


Figure 2. SIC&DH Location on HST

As in the actual SIC&DH, all the mock-up components mount to a structural tray to form the mock-up ORU. The tray used for the mock-up, shown in Fig. 5, has the same dimensions as the actual tray (25" x 33") however the mock-up tray has been simplified by modeling it as a plate of constant thickness rather than duplicating the intricate ribs and pockets of the actual tray. The mock-up tray does include the machined ears that are used to mount the ORU to the hinged door of the SSM. The mounting hole pattern of the original ORU tray has been kept intact although extra mounting holes have been added where necessary to support the design modifications for robotic servicing.

Only 10 (8 NSSCs and 2 RIUs) of the 17 electronic modules on the mock-up have been designed to be serviced. The other 7 modules are important to the overall mock-up because they provide the space restrictions that would be encountered in servicing the actual ORU. All of the modules that are not to be serviced are represented on the mock-up by folded sheet metal replicas which have the same dimensions as the actual ORU components. Most of the sheet metal components use internal fasteners to preserve the dimensions of the actual components and have removeable covers to provide access for mounting the components to the tray. The components that have been replicated out of sheet metal are shown in Fig. 6. The STINT/CPM stack, which consists of 4 modules on the actual ORU, is represented by a single sheet metal box that preserves the dimensions of the entire stack. The two CU/SDF modules

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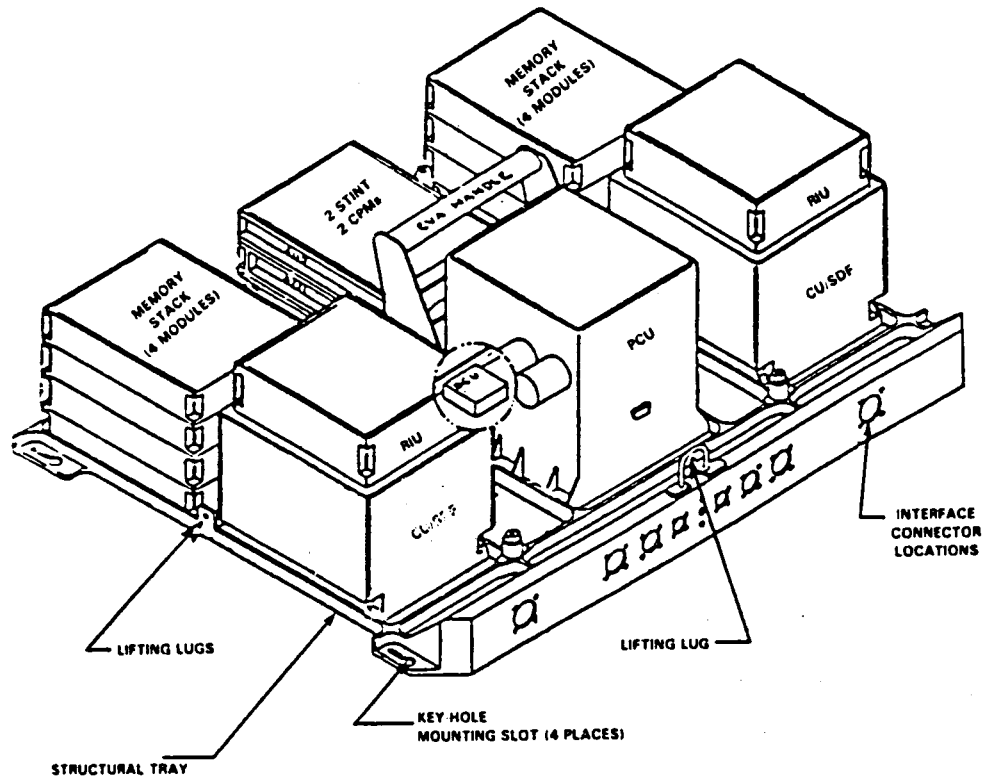


Figure 3. SIC&DH Component Layout

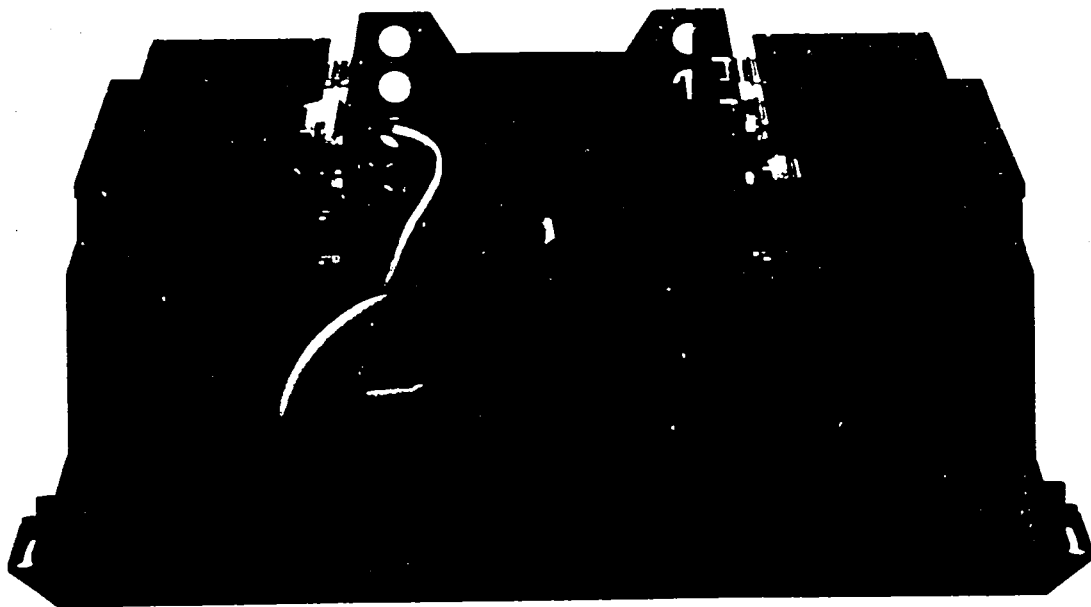


Figure 4. SIC&DH Mock-up

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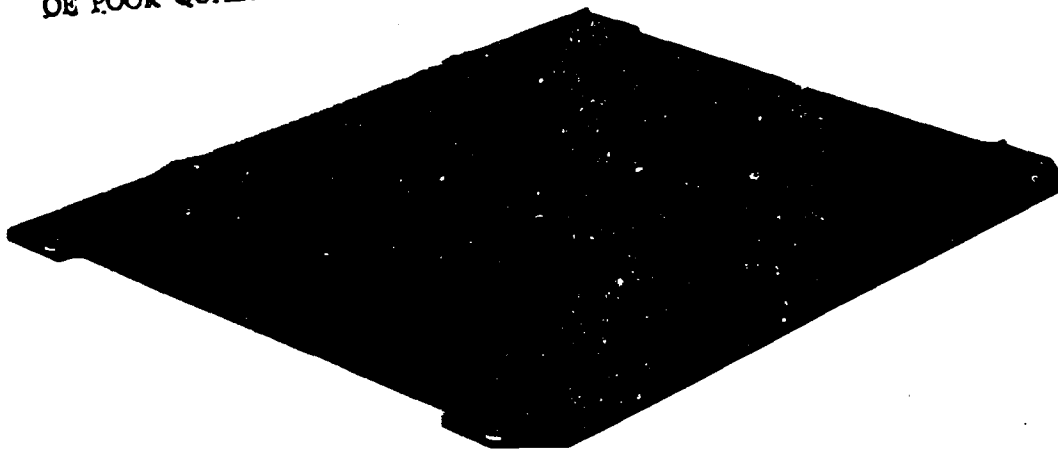


Figure 5. Mock-up Structural Tray

have threaded self-clinching fasteners in their covers to accommodate the RIU modules which mount on top. The PCU mock-up is slightly different from the other sheet metal components in that it has external mounting flanges so that an access cover was not necessary. Two other features of the SIC&DH ORU which have been represented on the mock-up by sheet metal structures are the EVA handle and the front panel of the tray which holds the interface connectors. The EVA handle and front panel are also shown in Fig. 6.

SERVICING METHODS

In order for the mock-up to realistically represent the re-design of the SIC&DH for robotic servicing, the functionality of the actual ORU had to be replicated. It was therefore necessary to identify the servicing constraints that would present themselves on the actual SIC&DH ORU and incorporate them into the mock-up. Mechanically this involved preserving the space limitations and mounting positions of the actual electronic modules on the ORU structural tray and keeping intact the overall dimensions and connector mating positions of the modules. Electronically, the constraints related to the use of a wire harness scheme for interconnecting modules and the use of Deutsch RM series and AMP HDD-22 subminiature connectors for the harness. The mock-up incorporates these features so as to serve as an accurate

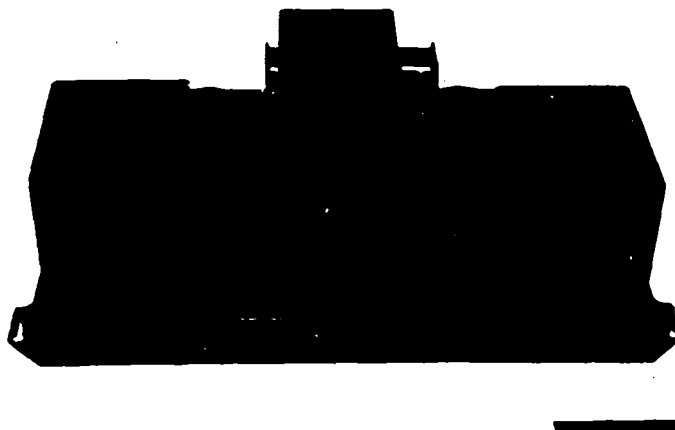


Figure 6. Sheet Metal Components on Mock-up

test of the requirements for servicing the SIC&DH ORU robotically. Three schemes were developed for servicing the electronic modules on the SIC&DH tray. These schemes are as follows:

1. Bus Method—Boxes are plugged into a fixed bus and then secured to the ORU tray.
2. Mechanism Method—Boxes are secured to the ORU tray and then a mechanism is used to mate the connectors.
3. Harness Method—Box is secured to ORU tray and then harness is mated to box.

It was decided that the mock-up should include all three methods in order to test out the validity of each scheme. A detailed description of each method and the hardware built for it is given below.

BUS METHOD

The bus method of servicing is accomplished by securing the wire harness to the structural tray and then mating the modules to the harness. In this method, the wire harness for a particular stack of electronic boxes runs to a rigid fixture which isolates the wire harness from loads applied to the connectors. The stack is assembled by plugging each module into the connectors on the bus fixture and then fastening it securely in place. The module stack is disassembled by reversing this procedure. In this method, the modules are mated by one robot arm and the other arm fastens the module to the stack. The bus method is used to service one of the two memory stacks on the mock-up. The memory stack consists of four identical modules each having two connectors apiece. Fig. 7 shows the location on the mock-up of the memory stack and fixture used for the bus method.

The fixture that was built to test out the bus method is shown in Fig. 8 along with its memory module stack. The bus fixture has been designed to fit in the space available between the memory stack and the STINT/CPM stack next to it. The fixture consists of two side braces and front and back panels. The eight harness connectors are fixed to the front panel corresponding to the locations of the connectors on the memory modules. The front plate of the fixture has been designed to allow the connectors to float to account for slight positioning errors during mating. Although the original memory modules for the SIC&DH tray made exclusive use of Deutsch 44 pin subminiature connectors, two of the memory modules are fitted with AMP type connectors to test the general feasibility of this method using different connector types. Also designed and built for this application were special shells that replace the original shells on the Deutsch connectors. The replacement shells are larger than the original ones and have a beveled outer lip to facilitate alignment during mating, however these are to be used only if problems are encountered with the standard shells.

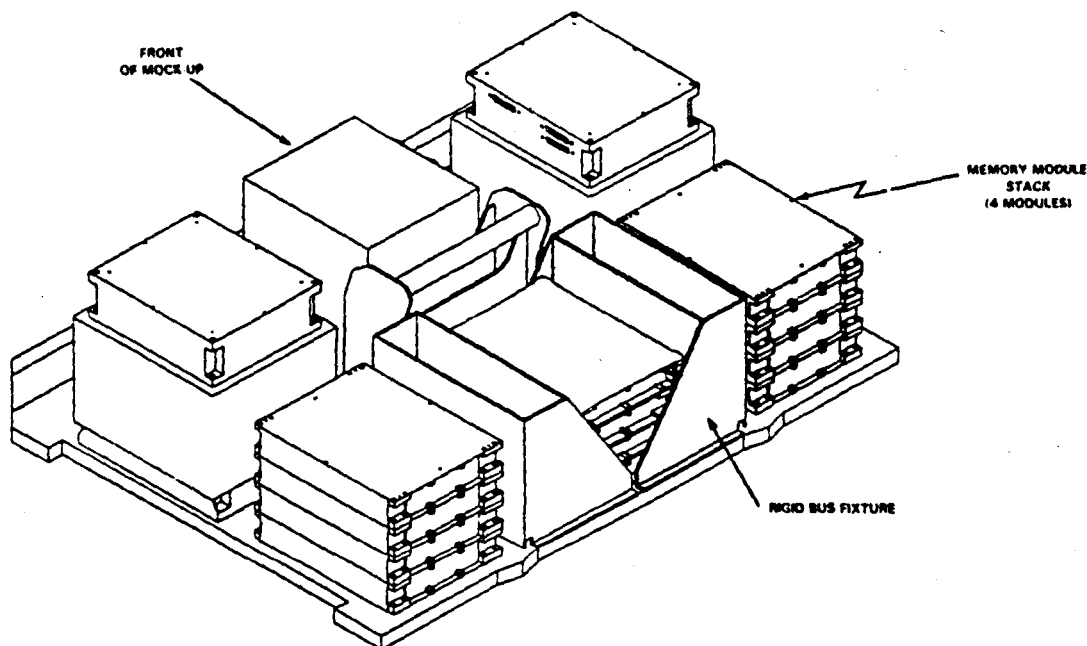


Figure 7. Location of Bus Method Hardware on Mock-up

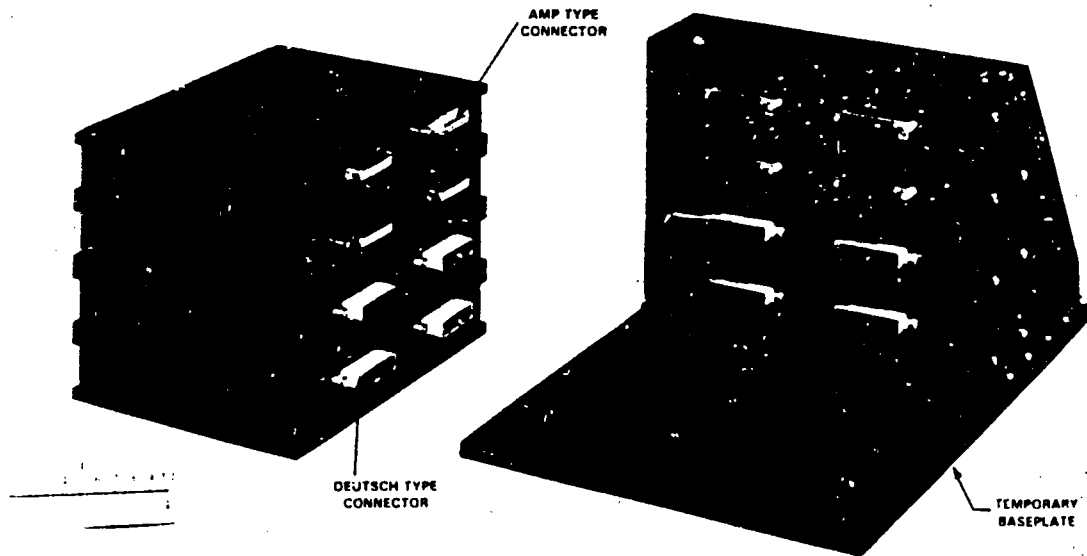


Figure 8. Bus Fixture and Memory Module Stack

The memory modules designed to be used with the bus fixture were based very closely on the original SIC&DH memory modules. The mock-up modules have similar external details as the original modules with approximately the same weight characteristics. No attempt was made, however, to simulate the internal electronics. For ease of fabrication, the mock-up modules consist of two parts, a housing machined from a single piece of aluminum and a sheet metal cover. The original modules were constructed from 4 side pieces with a top and bottom cover. Fig. 9 is an exploded view of one of the memory modules showing the cover, housing, and external features.

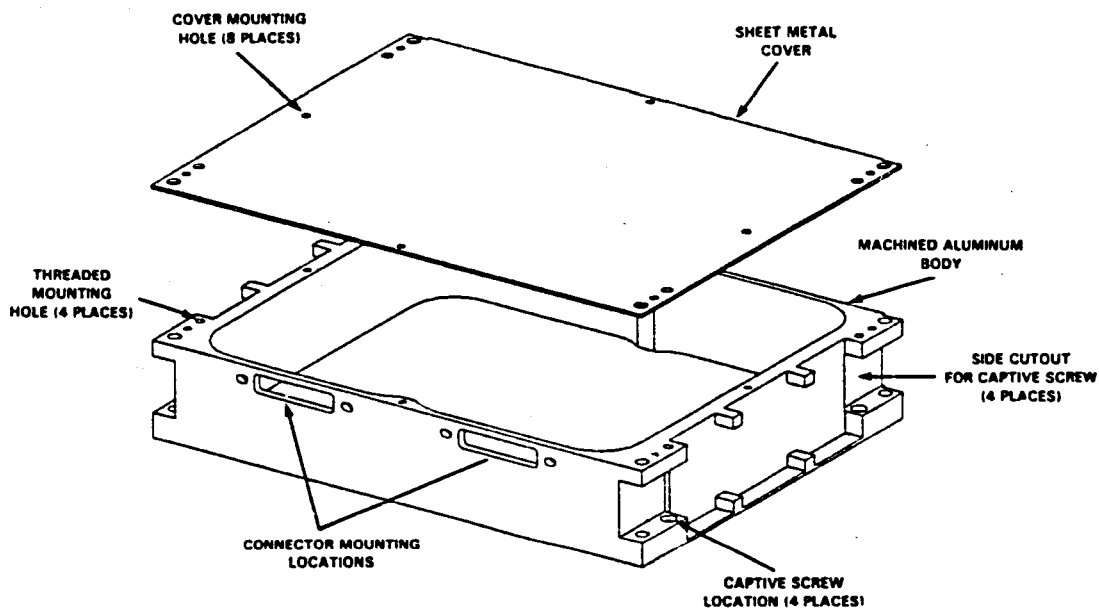


Figure 9. Mock-up Memory Module

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The mock-up memory modules have been modified to make use of a specially designed captive screw assembly for mounting. Each module makes use of four of these captive screw assemblies. Fig. 10 shows a detail of the assembly and its position on the module. The captive screw assembly consists of a stainless steel shell, a captivated socket cap screw, and a spring. The shell is machined from standard hexagon stock for ease of installation and serves to prevent lateral motion of the screw head during operation by the robot. The lower portion of the shell is threaded to mate with tapped holes in the module corners. The captivated screw is a standard button head socket cap screw which has been modified by undercutting a portion of the threads. The button head cap screw was chosen because space limitations required a low profile head and the size of the hex slot on the button head screw made it possible to operate the fastener by inserting a tool through the threaded holes at the top of the module. The spring is used to hold the screw up inside the shell to prevent damage to the screw threads during manipulation of the module. The captive screw assembly was designed to allow operation from the top and to permit interchangeability of modules. The shell, screw, and spring form an integral unit which can easily be incorporated into the design of similar type modules to allow for robotic servicing.

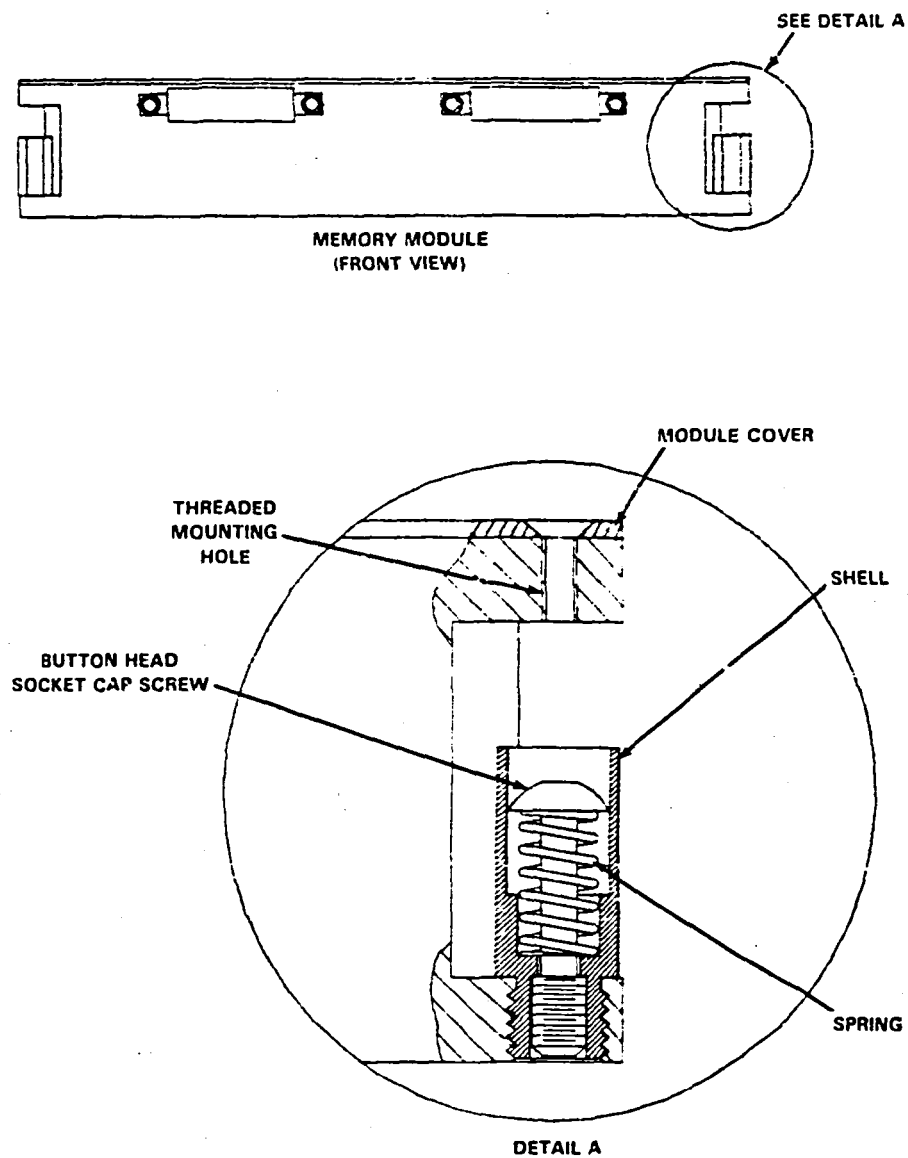


Figure 10. Detail of Captive Screw Arrangement

The other major change from the actual modules is that the mock-up modules have been designed to accommodate both the Deutsch and AMP connectors. This was accomplished by modifying the mounting holes and using threaded spacers in place of machined bosses for mounting the connectors to the modules. The threaded spacers can be positioned for either type of connector and also make it possible to replace connectors without having to remove the module cover. Fig. 11 shows the connector mounting arrangement developed for the mock-up modules.

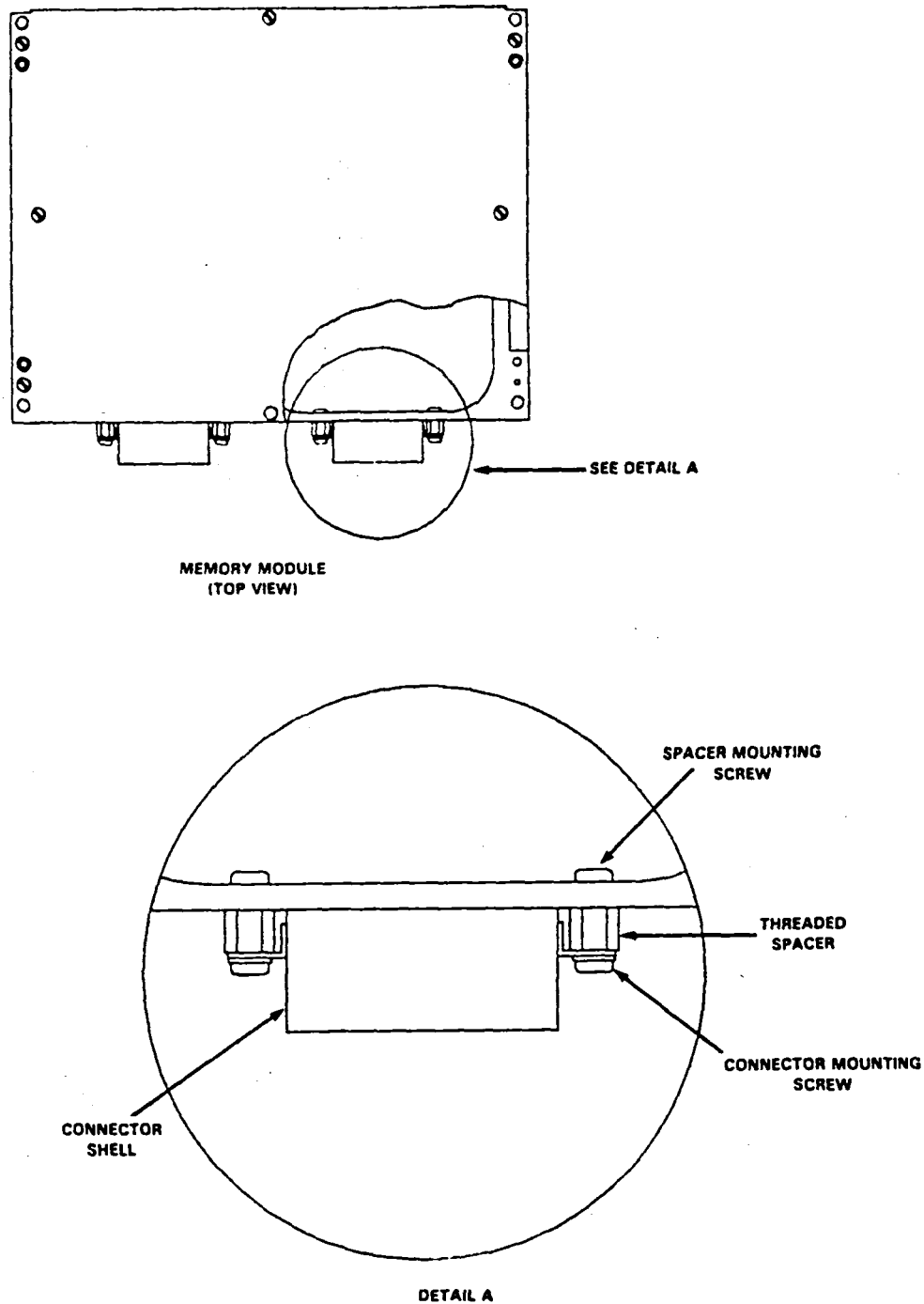


Figure 11. Detail of Connector Mounting Arrangement

The development of the hardware for the bus method was influenced by several design considerations. The close proximity of module stacks on the SIC&DH tray restricted the working envelope of the robot to the area above the memory stack. This prompted the development of a captive screw arrangement which could be operated from the top of each module. The design of the captive screw was also influenced by the restriction that the screw fit within the dimensions of the actual memory module. Space limitations also influenced connector selection as many of the blind-mating connectors currently used in the design of EVA serviceable hardware, such as G&H type connectors, were too large because they use oversized shells to provide positive alignment before mating occurs. The use of standard connectors was also a reflection of the desire to limit the impact of robotic servicing on the hardware design as was limiting connector float to the fixture side only.

MECHANISM METHOD

The mechanism method for servicing electronics modules involves assembling the module stack and then using a mechanical device to mate the wire harness to the stack. The connectors on the wire harness side are fixed to a plate that is constrained to move horizontally. One robot arm is used to position a module on the stack and the other arm secures it in place. Once the stack has been assembled in this manner, a mechanism is activated by one of the robot arms to move the plate with the harness connectors and provide the force necessary to mate the entire stack. The mechanism method differs from the bus method in that the alignment and mating of the harness to the module stack is accomplished by the operation of the mechanism and is not dependent upon the positioning capabilities of the robots. The function of the robot arms in this method is to assemble the module stack and to provide power input to the mechanism. The mechanism method is used with the other stack of memory modules on the mock-up ORU. Fig. 12 shows the location on the ORU tray of the fixture and modules for the mechanism method.

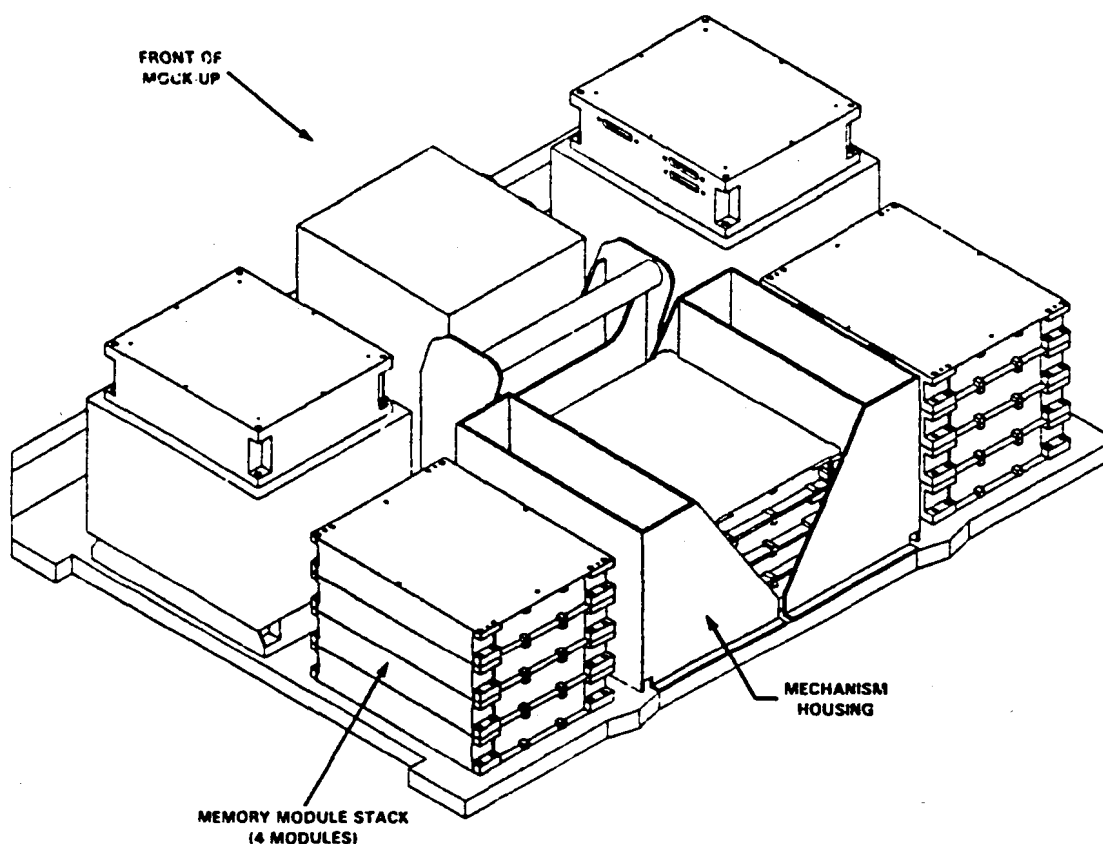


Figure 12. Location of Mechanism Method Hardware on Mock-up

The mechanism housing was designed with the same dimensions as the fixture used in the bus method because the space restrictions of both memory stacks are identical. This allows the mechanism housing to make use of the same support plate design as the bus fixture and gives both structures the same hole patterns for mounting to the tray. Fig. 13 shows the mechanism and housing that was developed for this servicing method. The front panel of the bus method fixture has been replaced by two panels in the mechanism housing. The outer plate is fixed and has cutouts through which the harness connectors can move. The moveable inner plate, to which the harness connectors are mounted, is constrained to move horizontally by two pins which are fixed at opposite corners of the inner plate and run through bushings in the outer plate. The rear plate has been modified to hold a worm and wheel gear mechanism which drives a standard 10 TPI Acme screw to which the inner plate is attached. A detail of this mechanism is shown in Fig. 14. The gearbox has a 70:1 ratio and has been rated to supply a mating force of up to 1000 lbs. Based on manufacturer information, the average mating force per connector is approximately 12 lbs so that mating an eight connector memory stack, would require around 100 lbs of force.

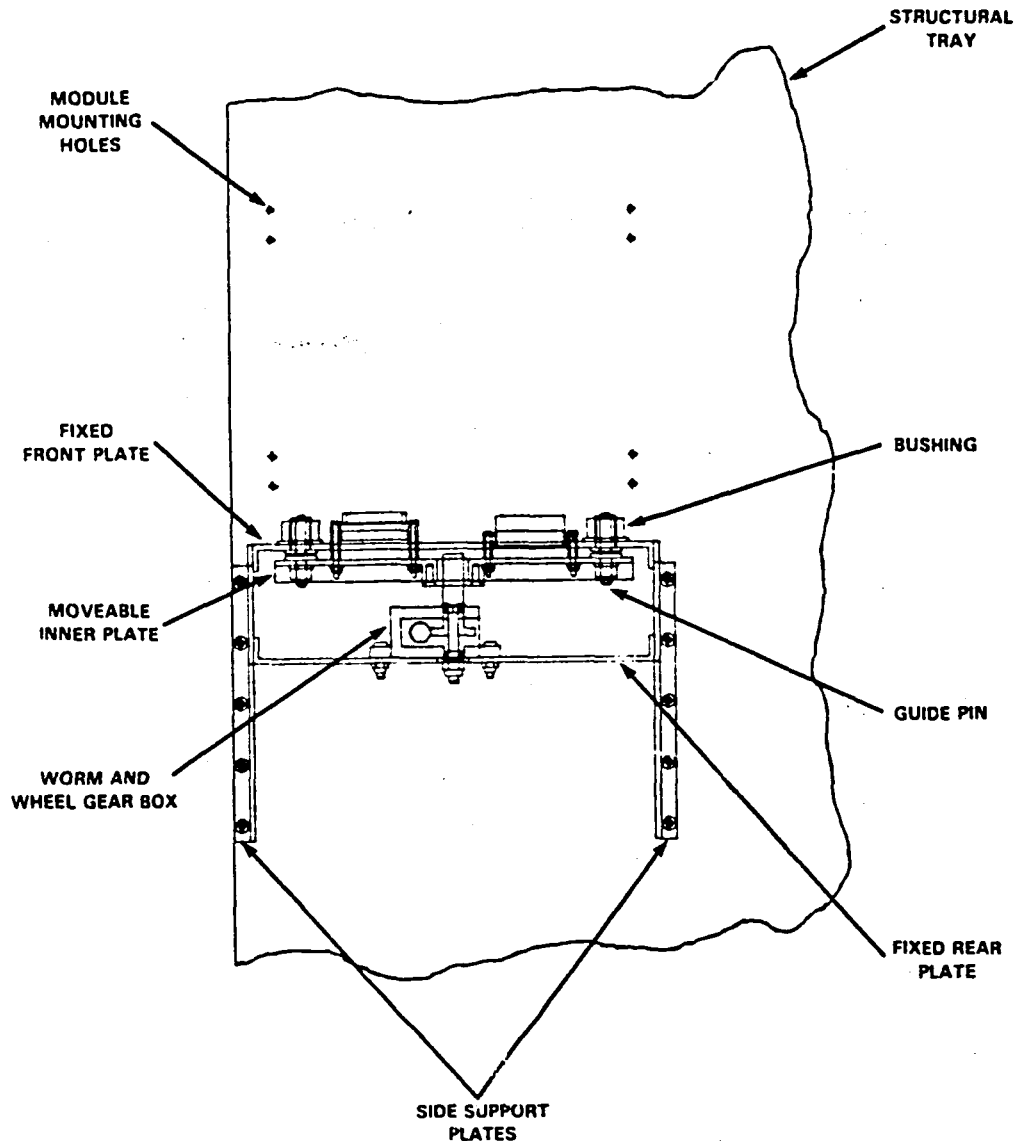


Figure 13. Mechanism Housing and Gearbox (Plan View)

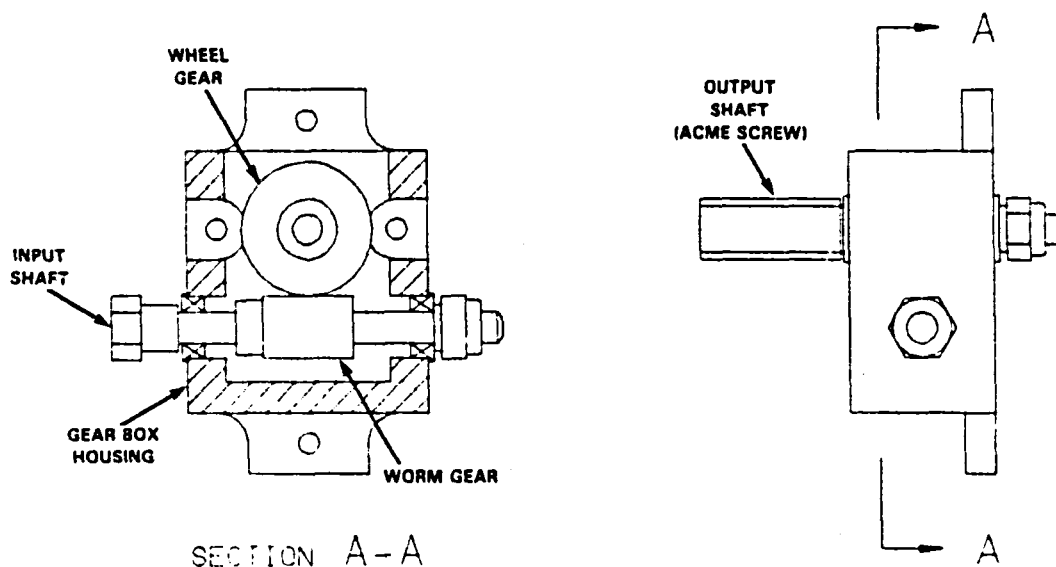


Figure 14. Detail of Mechanism Gearbox

The mechanism approach makes use of the same modules developed for the bus method. This was possible because the two memory stacks on the actual HST ORU are identical. Using the same modules cuts down on the number of tools required to service the mock-up. Identical modules also make it easier to directly compare the mechanism and bus methods as possible schemes for servicing stacks of electronic modules. With interchangeable modules in each memory stack, it is possible to test the planning software's ability to handle a number of different servicing scenarios such as removing a module from one stack and adding it to the other.

There were several considerations that influenced the design of the mechanism and housing that were built for this servicing method on the mock-up. The layout of the ORU tray not only limited the size of the mechanism housing but also required that the mechanism be operated from the top of the housing. This requirement along with the fact that the device was to be operated by a single robot arm (ie. single input source) and had to be self-locking upon removal of input power led to the use of a power screw mechanism with a worm and wheel gearbox. This type of gearbox prevents the mechanism from being back-driven and also provides the means to operate the power screw from the top because it allows the output load to be applied perpendicular to the input torque. The design of the gearbox was constrained by the fact that it had to fit within the space available for the mechanism housing and provide sufficient force for mating the connectors.

HARNESS METHOD

The Harness method is the final servicing technique that is to be examined on the SIC&DH mock-up. It involves direct manipulation of the wire harness by the robots. In this method, the memory stack is assembled by mounting the modules to the tray in the same manner as in the mechanism method. The robots then retrieve the wire harness from a storage fixture and perform the mating operations. The memory stack is disassembled in the reverse order by having the robot arms remove the wire harness from the stack, place it in a storage fixture and then remove the modules from the stack. The harness method is used to service the two RIUs on the mock-up. For the purposes of the mock-up, the wire harness has been simulated using standard multi-wire cable which runs from a connector location on the RIU to the ORU tray. The location of the RIUs and wire harness on the mock-up is shown in Fig. 15.

The mock-up RIU module created for this method, shown in Fig. 16, is similar in construction to the modules built for the other two servicing methods. The mock-up RIUs make use of the captive screw arrangement in order to limit the different types of tooling required for servicing. The mock-up RIUs differ from the actual modules in that only three of the eight connector mounting locations have been represented on the front of the module and these have been modified to allow the mounting of either the AMP or Deutsch connectors. While the present test of the harness method will require only one connector location on the mock-up RIU, two additional mounting locations have been added to provide the flexibility to expand the mock-up later on.

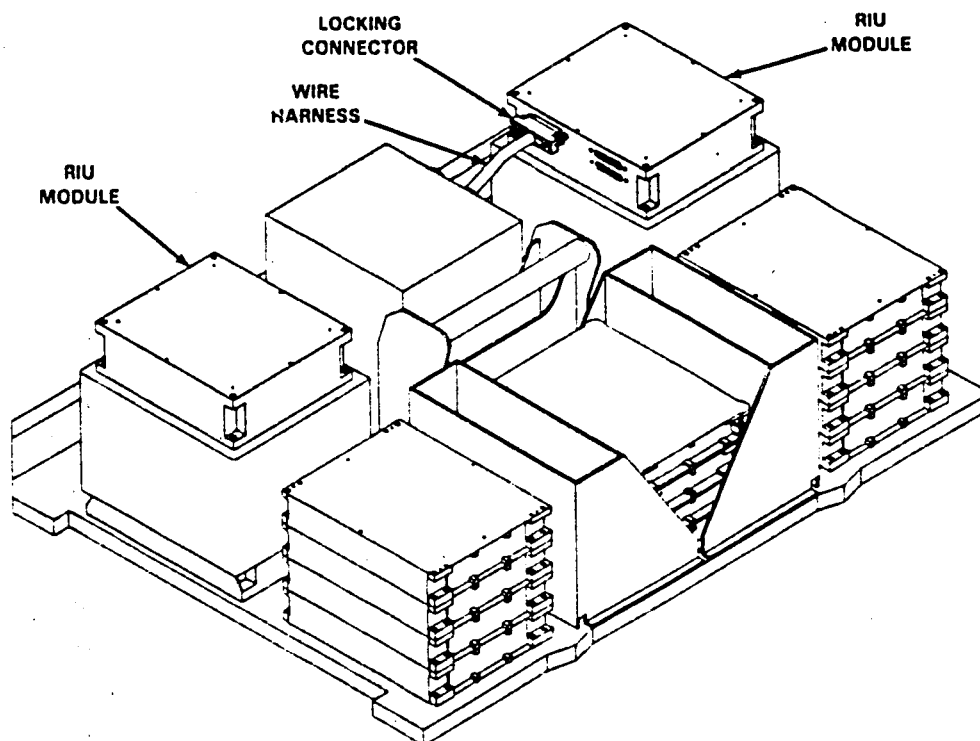


Figure 15. Location of Harness Method Hardware on Mock-up

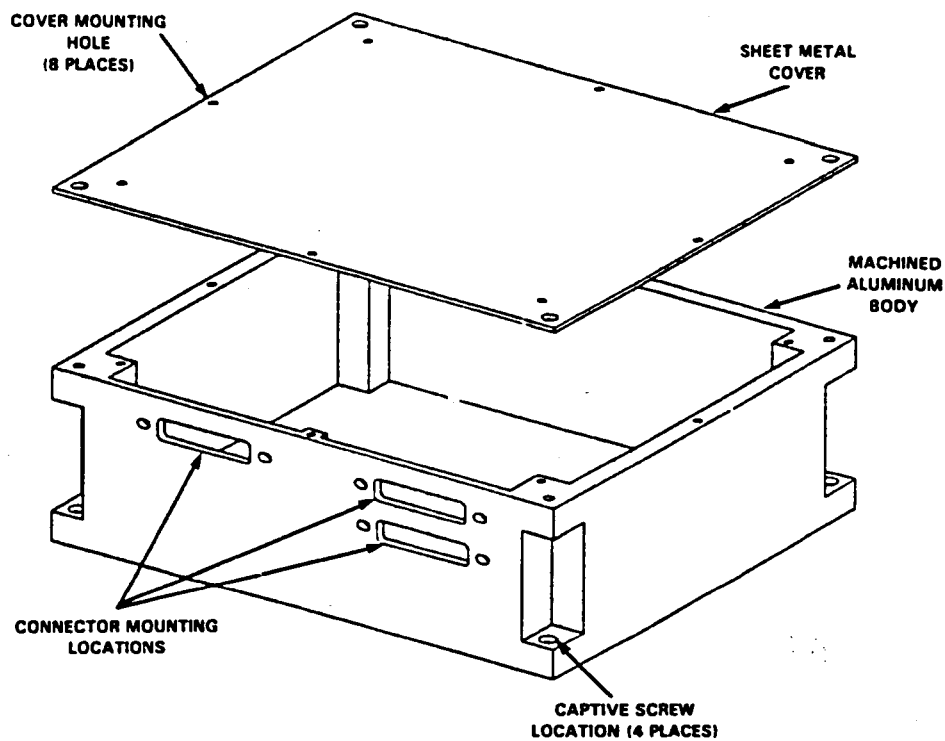


Figure 16. Mock-up RIU Module

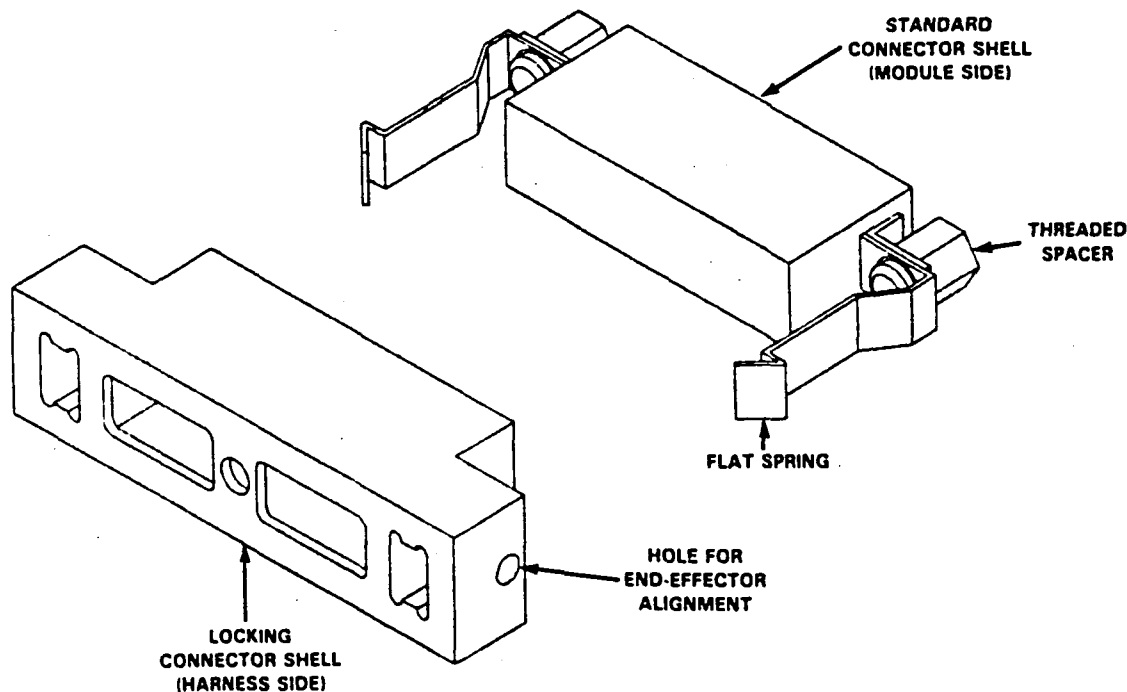


Figure 17. Locking Connector for Harness Method

The harness method requires a connector that locks securely in place once mated and yet can be easily unlocked for removal. The original Deutsch connectors have been given this capability by the design of a new connector shell that replaces the existing shell on the harness side and is used in conjunction with flat springs that mount to the connector on the module side. The locking connector shell and flat springs are shown in Fig. 17. The positive locking feature is provided by the flat springs which slide through openings in the connector shell and engage the rear of the shell when mated. The connectors are demated by pushing the springs inward until they are clear of the rear of the connector shell and then pulling the connector halves apart. A special set of robot gripper jaws will be used to accomplish this task. The jaws will engage notches on the side of the connector shell for alignment and will be designed so that when they are fully closed, the springs are disengaged from the shell and the harness connector can be demated from the module.

Manipulation of the wire harness requires that the harness connectors be rigidly supported at all times to ensure that the location of the harness is known to the robot. This means that mating operations using this method must take into consideration the length of the harness and the location of all the connectors on the harness. This task becomes very complicated when trying to mate a harness that interconnects a number of electronic modules each with several different connector locations. The most straightforward application of the harness method is to the case where the wire harness runs between only two connector locations. It is at this situation that the SIC&DH mock-up for the harness method is directed.

The requirements of servicing electronics modules using the harness method affected the development of the mock-up in many ways. The decision to study only the point-to-point harness case was a result of examining the capabilities of this servicing method within the scope of the research. The positive locking capability, which requires a modification to the Deutsch connector on the harness side only, was developed based on the guidelines to use standard connectors and to limit the effect that implementing the harness method would have on spacecraft design.

CONCLUSION

The ability to perform on-orbit autonomous robotic servicing of spacecraft and satellites requires not only the development of intelligent robots that are technologically capable of performing unassisted servicing operations but also requires an understanding of how spacecraft can be designed to facilitate robotic servicing. The robotics research being conducted at GSFC is an attempt to examine the concepts and consequences of designing spaceflight hardware to be serviced robotically. The focus of this research is to develop a set of guidelines which pinpoint areas of concern in the design of robotically serviceable hardware. The mock-up developed by this effort represents the application of an initial set of design guidelines to an actual spacecraft system. Three techniques for the servicing of electronic modules which fulfill the identified design guidelines are presented on the mock-up. Testing of the mock-up to be done at GSFC and the Jet Propulsion Laboratory (JPL) will examine the validity of each of the servicing methods and allow for the verification and refinement of the design guidelines for autonomous robotic servicing.



Report Documentation Page

1. Report No. NASA TM-100700		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Design Guidelines for Robotically Serviceable Hardware				5. Report Date April 1988	
				6. Performing Organization Code 731.0	
7. Author(s) Scott A. Gordon				8. Performing Organization Report No. 88E0163	
				10. Work Unit No.	
9. Performing Organization Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract This report details the research being conducted at the Goddard Space Flight Center into the development of guidelines for the design of robotically serviceable spaceflight hardware. A mock-up has been built based on an existing spaceflight system that demonstrates how these guidelines can be applied to actual hardware. The report examines the basic servicing philosophy being studied and how this philosophy is reflected in the formulation of design guidelines for robotic servicing. A detailed description of the mock-up is presented with emphasis on the design features that make it "robot friendly". Three robotic servicing schemes that fulfill the design guidelines were developed for the mock-up. These servicing schemes are examined and how their implementation was affected by the constraints of the spacecraft system on which the mock-up is based.					
17. Key Words (Suggested by Author(s)) Robots Robotics Spacecraft Design				18. Distribution Statement Unclassified - Unlimited Subject Category 18	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 21	
22. Price					

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Block 12. Sponsoring Agency Name and Address. National Aeronautics and Space Administration, Washington, D.C. 20540-0001. If contractor report, add NASA installation or HQ program office.

Block 13. Type of Report and Period Covered. NASA formal report series; for Contractor Report also list type (interim, final) and period covered when applicable.

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